General Electric (GE) Global Research

Increased Fuel Efficiency and Decreased Emissions Through TBCs

The ability to achieve high fuel efficiency gives turbine manufacturers one way to gain a competitive advantage in the electricity marketplace. In particular, efficiency is an important factor in increasing the generating capacity of power plants. The maximum efficiency for a General Electric (GE) gas turbine engine in 1995 was 54.5 percent. In order to improve efficiency and reduce operating costs for its turbines, GE wanted to raise the firing temperature of its gas-fired turbine engines. By applying thermal barrier coatings (TBCs) onto hot-path turbine engine components, turbines could operate at higher temperatures, thereby increasing efficiency without reducing component life. However, GE researchers could not be certain that high-performance TBCs could be produced reliably with the durability required to withstand harsh operating conditions. GE submitted a proposal to receive funding from the Advanced Technology Program (ATP) because the technology development project was beyond the scope of research and development efforts funded by other Federal research programs and GE's internal research and development budget.

In 1995, GE was awarded funding for the project as part of the ATP focused program, "Materials Processing for Heavy Manufacturing." GE's successful project fostered a scientific, integrated, structured approach to the development of thermal spray technology, which could also be used by the steel, automotive, aircraft, biomedical, and paper industries. Project researchers developed thermal spray technologies used to produce high-performance TBCs that contributed to an upgraded version of GE's 1996 F-series power plant model, raising its 54.5-percent efficiency to 56 percent. TBCs made a critical contribution to the development of the next-generation H-series gas turbine engine, which can achieve 60-percent efficiency (the first commercial model was delivered in 2000). As a result of these advancements, power plants consumed less fuel and reduced their emissions, and GE became a market leader in worldwide gas turbine production.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

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Research and data for Status Report 95-07-0018 were collected during April - June 2003.

Higher Temperature Increases Efficiency

The greatest barrier to using high temperatures in gas turbine engines is the rotating turbine blades' lack of durability. These and other components can be damaged when exposed directly to excessively hot gases. If engineers could attain higher temperatures, the engines would consume less fuel to generate electricity and would produce lower carbon dioxide (CO_2) emissions. In 1995, the state-of-the-art turbine engine was developed by General Electric (GE) and was based on jet engine technology. It allowed firing temperatures of up to 1300 °C, for a thermal efficiency of 54.5 percent. While GE did have a market-leading position, global competition was stiff, and GE needed to continue to make advances to protect its market share as well as U.S. jobs and U.S. economic growth.

TBCs Allow Higher Firing Temperatures

GE aimed to achieve higher firing temperatures and higher efficiency by protecting heat-sensitive components with an insulating "armor," called thermal barrier coatings (TBCs). TBCs are thin ceramic layers applied to component surfaces to insulate the surface alloy from hot gases, allowing engineers to design engines capable of operating at higher temperatures. TBCs help to increase efficiency and reduce emissions, without increasing downtime or maintenance costs.

Air-plasma-sprayed TBCs had been used on some gas turbine parts for more than a decade, but the industry lacked a reliable manufacturing process for applying these high-performance coatings onto high-temperature parts. The plasma spray process involves spraying a protective material, such as refractory ceramics (e.g., zirconia), in molten form onto a surface (substrate) to provide a protective, insulating TBC. The materials are injected as powders into a very-high-temperature plasma flame. The hot material impacts on the substrate and rapidly cools to form a coating that is approximately 0.1 to 2 mm thick.

Existing plasma-coating technology did not monitor all of the critical process conditions or TBC specifications (e.g., spray particle temperature and coating thickness) during spraying. Coating results could be inconsistent due to online disturbances, wear of spray gun parts, and spattering. Existing control systems monitored and regulated only the directly controllable, preset process variables. These variables, which were based on an operator's or a coater's experience, included gun current, gas flow rates, powder feed rates, gun speeds, spray distances, and spray angles. The control systems provided no objective, real-time feedback on the process and coating conditions.

GE requested funding from the ATP "Materials Processing for Heavy Manufacturing" focused program in order to apply rigorous scientific methods to measure and advance plasma-coating methods for the entire thermal spray industry. The company had a clear focus on a major manufacturing need: using TBCs to increase efficiency in power plants. However, it could take years to see any return on investment. Moreover, GE researchers could not be sure that high-performance TBCs could be deposited reliably on high-temperature components to meet the required lifetimes.

In this ATP-funded project, GE planned to develop an Intelligent Processing of Materials (IPM) technology for consistently applying high-quality TBCs using plasma coating. The IPM thermal spray technology has five elements: new plasma spray sensors, an empirical process-properties database, physics-based models, control algorithms, and process controllers. The sensors would provide feedback for developing and controlling thermal spray processes. The database and models would produce the quantitative link between the control parameters and the TBC properties. Control algorithms and the hardware for process control would enable real-time adjustments to the plasma spray process.

GE Developed an Aggressive Technical Plan

GE identified several technical risks in its proposal to ATP. Could multiple sensors on the spray equipment operate effectively together in a high-temperature environment? Could the data from the sensors be understood and analyzed efficiently? Could the control indicators be effectively identified and quantifiably mapped to results? Would an IPM control strategy be cost effective? Would IPM substantially improve coating performance?

To develop the IPM technology for high-performance TBCs, the project team worked on five tasks. These tasks and their results are described below:

1. ***Task***: Learn more about the plasma spray process by working with the National Research Council of Canada (NRC), a subcontractor, to consider and apply a robust set of control sensors to monitor numerous parameters. NRC is a leading expert in control sensor development for the plasma spray process.
   Result: The team selected and developed two sensors to measure component surface temperature and coating particle temperature. This impacted two critical TBC properties, elastic modulus and tensile strength.

2. ***Task***: Develop and populate an empirical database with data points from the sensors.
   Result: The team used the database results to generate a set of models for flat-plate substrates to connect process parameters with TBC properties.

3. ***Task***: Work with the University of Minnesota, a subcontractor, to develop a physics-based process model and useful control algorithms. GE had worked with this group before; they are leading experts in modeling the plasma process. The

plasma-particle interaction model would provide rules for the system controller to update the spray process parameters on-the-fly and to ensure that the coatings would meet specifications.
Result: The team developed and verified plasma, substrate-heating, and particle-heating models with production parameters.

4. ***Task***: Develop a process control model based on the results from Tasks 2 and 3. The system controller would use online feedback from the sensors to maintain quality control, reduce the process variations, and produce improved TBC properties.
Result: The team developed a control design toolbox to control the particle state and substrate temperature. This toolbox can be adapted to include newer process models and additional control modes.

5. ***Task***: Work with Sulzer Metco, a subcontractor, to provide the controller hardware and Ethernet communications to establish an interface between the sensors, controllers, and operators and to demonstrate the system.
Result: The team developed and demonstrated an integrated, expandable infrastructure for the IPM controller that accessed the process sensors and plasma controller via Ethernet communications. This included monitoring the particle state and the substrate temperatures recorded by the sensors in Task 1.

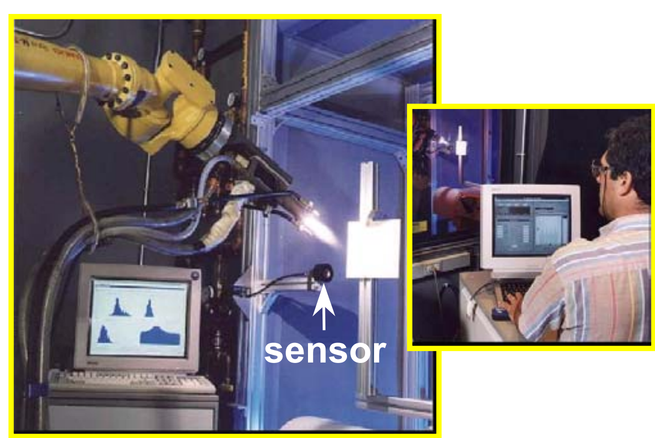
As a result of the ATP-funded project, GE and its subcontractors, University of Minnesota, Sulzer Metco, and the NRC, developed a method to improve the process for applying consistent, high-quality TBCs on hot-path engine parts. The thermal spray technology could also be applied to improve oxidation-resistant, corrosion-resistant, and wear-resistant coatings, which would have additional broad industrial applications through their ability to:

- Tolerate higher temperatures (increasing efficiency)
- Use less costly alloys for some construction materials (reducing the cost of production)
- Reduce consumption of fuel (reducing specific emissions of CO2)
- Reduce corrosion and wear (enhancing the part's life)

The ATP-funded project developed processes to apply TBCs on flat sample substrates. After project conclusion in 1998, GE still needed to transition the technologies to real, complex geometry parts. After the technical issues were resolved, GE would also need to conduct cost-benefit assessments as they implemented the program technologies in a phased approach.

Application of TBCs to Gas Turbine Engines Improves Efficiency

Following the completion of the ATP-funded project, GE conducted business and technology assessments and incrementally implemented the IPM technology. In addition, they used knowledge from parallel programs to apply TBCs to complex-shaped parts. GE was then able to apply IPM technology to develop improved thermal spray processes implemented for power plant production. To achieve higher operating temperatures, GE required better thermal performance throughout the hot sections of the turbine. To survive these high temperatures, super-alloy components would be coated with enhanced, high-performance TBCs. GE assembled a multidisciplinary team to improve thermal spray technology for depositing high-performance TBCs on hot-path engine components.



The GE intelligent plasma spray process: A robot moves the plasma gun while sensors mounted in the sensor head monitor the speed, angle, and other parameters. The operator monitors the results on a Windows-based screen and makes real-time adjustments.

In 1999, GE introduced an upgraded version of its existing F-System combined-cycle gas turbine, which operated at 56-percent fuel efficiency. The increases in firing temperature and efficiency were accomplished in part through the expanded use of enhanced TBCs on key components.

By December 2000, GE had delivered its first H-System combined-cycle gas turbine, the latest development in power-generation technology. This engine demonstrated a technology that could achieve 60-percent efficiency. The engines firing temperature increased to 1430 °C (up from 1300 °C) and used a steam-cooling cycle, among other advances. Closed-loop, steam cooling results in higher thermal stresses on the airfoil materials, so GE used single-crystal super-alloys, in conjunction with high-performance TBCs, on the flow-path surfaces of the steam-cooled turbine airfoils.

GE researchers could not be sure that high-performance TBCs could be deposited reliably on high-temperature components to meet the required lifetimes.

As of 2004, GE continues to develop the TBC technology that originated during this project. The improved thermal, wear, and corrosion-protection qualities of the thermal spray coatings can raise the level of U.S. competitiveness in the aircraft, automotive, steel, pulp and paper, electronics, and biomedical industries.

Improved TBCs Strengthen GE's Market Position

GE had a 34-percent market position in sales of gas turbines for power generation in 1995, a market that was growing at a rate of 2 percent annually. This project took place prior to the beginning of deregulation in the domestic U.S. energy market in 1998. Power plant sales were weak as U.S. companies anticipated regulatory changes. "Energy efficiency was critical to remaining competitive in a soft market and to preparing for anticipated significant growth, once the new requirements would become clear," said Dr. James Ruud of GE Corporate Research and Development. To protect GE's market position and to retain or increase the number of manufacturing jobs, U.S. manufacturers had to maintain technical superiority of turbine engines through three market differentiators: low initial cost, high efficiency, and low maintenance cost.

A 1-percent improvement in engine efficiency can save $20 million in fuel over the life of a typical gas-fired 400- to 500-megawatt combined-cycle plant.

The slow period immediately preceding the 1998 deregulation of the U.S. domestic power market allowed GE to test the use of TBCs in their turbine manufacturing facilities. GE geared up production in anticipation of deregulation and benefited from the process improvements in this project. Deregulating the U.S. energy market led to a sales "bubble" from 1999 to 2002, and GE was able to increase production of TBCs to meet this demand.

GE continues to be the dominant world leader in gas turbine manufacturing; its global market position grew to 48 percent in 1997, 53 percent in 1999, and 64 percent in 2001. Global gas turbine power system sales totaled $101 billion in 2000, but dropped 20 percent in 2001 due to the global economic downturn. GE's power division sales grew from $8.0 billion in 1997 to nearly $23 billion in 2002, in spite of an overall economic slowdown. And, most importantly, GE's installed power plants are operating at higher efficiency, thereby reducing fuel cost, generating less pollution, and saving money for industry and consumers.

The present supply of power in the United States is inadequate to meet the nation's projected demand for electric power through 2020. Therefore, the anticipated market for power plant modernization and new construction is relatively strong, especially compared with U.S. manufacturing as a whole. In the face of foreign competition, GE has developed the right combination of advanced materials, design, and manufacturing technology to continue to grow.

Efficiency Benefits the U.S. Economy

Gas turbine engines used in power plants consume vast amounts of fuel. Therefore, improving fuel efficiency by even a minute amount contributes to reducing the cost of electricity in the United States and protecting U.S. jobs. For example, a 1-percent improvement in engine efficiency can save $20 million in fuel over the life of a typical gas-fired 400- to 500-megawatt combined-cycle plant. Moreover, environmental benefits accrue in the form of reduced emissions of nitrous oxide (NOx) and carbon dioxide (CO2).

This project also positively impacted the U.S. thermal spray industry. The thermal spray market segment for industrial gas turbines was growing at approximately 10 percent per year in the mid- to late 1990s, but it was negatively affected by the changes in the U.S. economy. Potential for growth still remains; for example, the worldwide market in 2002 for applying TBCs to turbine engine components exceeded 1 million units per year. With an average cost of $200 per unit, the market for applying TBCs in turbines was approximately $200 million annually.

An additional market for thermal spray coatings is the 14 million diesel engines operating in the United States. The potential market for diesel-engine coating retrofits or rebuilds could be as large as $150 million. Unfortunately, the major market for the U.S. thermal spray manufacturers is the U.S. manufacturing industry, which has experienced a 15-percent decline in employment since 2000. The manufacturing industry continues to suffer, due to the worldwide economic downturn since 2001, especially in the aircraft industry. In addition, foreign outsourcing to Mexico and especially China has hurt U.S. manufacturing as a whole. Thermal spray industry representatives hope that their business will grow again as companies seek to retrofit, rebuild, and improve the efficiency of their engines.

GE Disseminates TBC Knowledge

The GE team provided expertise in controls, manufacturing sensors, materials, and modeling. This knowledge was disseminated throughout the TBC industry through publications, workshops, and symposia for the thermal spray community.

Conclusion

In 1995, the highest fuel efficiency available in a combined-cycle, gas turbine power plant was 53.5 percent. This successful ATP-funded project resulted in an integrated, expandable intelligent process to apply high-performance thermal barrier coatings (TBCs) in gas turbine engines for power plants. The high-performance TBCs developed in part using that technology contributed to General Electric's (GE) ability to achieve 56-percent power plant efficiency in 1999 and to demonstrate a technology that achieved 60 percent efficiency in 2000. The project researchers used chemistry, engineering, statistical analysis, and manufacturing processes to systematically seek solutions to the process of applying TBCs to hot-path mechanical alloy parts. The team shared these methods with the thermal spray industry for use in other industries, such as aircraft and heavy manufacturing.

PROJECT HIGHLIGHTS
General Electric (GE) Global Research (formerly GE Corporate Research and Development)

Project Title: Increased Fuel Efficiency and Decreased Emissions Through TBCs (Intelligent Processing of Materials (IPM) for Thermal Barrier Coatings [TBCs])

Project: To develop an "intelligent process" for applying ceramic thermal barrier coatings (TBCs) on hot components of turbine engines used for generating power to improve the engines' efficiency, power production, emissions, and lifetime.

Duration: 9/1/1995-8/31/1998
ATP Number: 95-07-0018

Funding (in thousands):**

ATP Final Cost	$1,595	48.8%
Participant Final Cost	1,676	51.2%
Total	$3,271	

Accomplishments: By the end of this ATP-funded project, the team of General Electric (GE) and its three subcontractors had successfully completed all its tasks and had met all its milestones. The team developed an integrated, expandable Intelligent Processing of Materials (IPM) controller, which improved the TBC properties.

GE's work on this project contributed to significant knowledge sharing in the thermal spray community. GE communicated the program accomplishments internally and externally at strategic times. During 1997 and 1998, they held two day-long workshops, which were open to the thermal spray community. They described their progress, which was based on this project and on parallel programs, on sensors and control for the thermal spray process. Attendees represented 21 different companies and universities, including heavy industry, coating vendors, and thermal spray equipment and sensor manufacturers. GE also visited three manufacturing and repair sites that use thermal spray. They gave conference presentations and provided process technology to other programs covering sensor and data acquisition software, the monitoring system, and the use of historical data to capture and interpret TBC results.

During and after the ATP-funded project, GE has continued to share its extensive expertise and knowledge through conferences, including the following:

- Park, J.H., Z. Duan, J. Heberlein, E. Pfender, Y.C. Lau, and H.P. Wang. "Modeling of Fluctuations Experienced in N2 and N2H2 Plasma Jets Issuing into Atmospheric Air." Proceedings of the 13th International Symposium on Plasma Chemistry, August 18-22, 1997, vol. I, pp. 326-331. Ed., C. K. Wu. Beijing: Peking University Press.

- Park, J.H., J. Heberlein, E. Pfender, Y.C. Lau, J. Ruud, and H.P. Wang. "Particle Behavior in a Fluctuating Plasma Jet." Proceedings of the 2nd International Symposium on Heat and Mass Transfer Under Plasma Conditions, April 19-23, 1999, Antalya, Turkey. vol. 891, pp. 417-424. Ed., P. Fauchais, J. van der Mullen, and J. Heberlein. New York Academy of Sciences.

- Symposium on "Thermal Spraying-Materials Synthesis by Thermal Spraying." Materials Research Society, Fall Meeting, November 1999.

- Park, J.H., E. Pfender, and C.H. Chang. "Reduction of Chemical Reactions in Nitrogen and Nitrogen-Hydrogen Plasma Jets Flowing into Atmospheric Air." Plasma Chem. Plasma Process, 20(2) pp. 165-181, 2000.

- Symposium on "High-Temperature Thermal Spray Coatings: Thermal Barrier Coatings." Materials Research Society, Fall Meeting (sponsored by General Electric Global Research Center and Sulzer Metco, Inc.), December 2002.

- Symposia on "Controls and Sensors for Thermal Spray Processes" and "Gas Turbine Coating Symposium." International Thermal Spray Conference, May 2003, Orlando, FL; GE's Dr. Y.C. Lau was the symposia co-organizer.

Commercialization Status: GE successfully produced an improved gas turbine engine for its new H-System combined-cycle power plant, which can achieve 60-percent energy efficiency. The high-performance TBCs developed in part using technology from this project were essential to the design of this model. GE also applied the knowledge to upgrade existing F-System plants, which achieved 56-percent efficiency. Other companies have used the process on marine aircraft and heavy diesel engines, as well as other applications.

** As of December 9, 1997, large single applicant firms are required to pay 60% of all ATP project costs. Prior to this date, single applicant firms, regardless of size, were required to pay indirect costs.

PROJECT HIGHLIGHTS
General Electric (GE) Global Research (formerly GE Corporate Research and Development)

Outlook: The outlook for IPM of TBCs and other thermal spray coatings is excellent. Global demand for power is increasing. Significant growth is anticipated over time, depending on world economic health. Continued strong global economic health will assure the continued need to improve existing plant efficiency and to construct new power plants. In addition, the thermal spray technology advances are continuing to spread through the automotive, marine, aircraft, and diesel engine markets.

Composite Performance Score: * * *

Focused Program: Materials Processing for Heavy Manufacturing, 1995

Company:
General Electric Global Research
P.O. Box 8
Schenectady, NY 12301

Contact: Dr. James Ruud, Project Manager
Phone: (518) 387-7052

Contact: Dr. Y. C. Lau, Principal Investigator
Phone: (518) 387-6017

Contact: Vince Kwasniewski
Phone: (630) 961-7403

Subcontractor:
University of Minnesota
Department of Mechanical Engineering
111 Church Street SE
Minneapolis, MN 55455-0111

Sulzer Metco (US) Inc.
1101 Prospect Avenue
Westbury, NY 11590-0201

National Research Council of Canada
NRC Corporate Communications
1200 Montreal Road, Bldg. M-58
Ottawa, Ontario
Canada K1A 0R6

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